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# Effects of Windblown Dust on Photovoltaic Surfaces on Mars

James R. Gaier and Marla E. Perez-Davis  
*Lewis Research Center*  
*Cleveland, Ohio*

and

Alia M. Moinuddin  
*Case Western Reserve University*  
*Cleveland, Ohio*

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**NASA**

James R. Gaier and Marla E. Perez-Davis  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

and

Alia M. Moinuddin  
Case Western Reserve University  
Cleveland, Ohio 44106

## ABSTRACT

Photovoltaic (PV) coverslip material was subjected to Martian dust storm conditions using basaltic dust flowing through the Martian Surface Wind Tunnel at NASA Ames Research Center. Initially dusted and initially clear coverslips were held at angles from  $0^\circ$  to  $90^\circ$ , and the dust laden wind velocity was varied from 20 to 97 m/s. Blowing dust was found to adhere more to the coverslips as the angle was increased. However, dust was partially cleared from surfaces that were initially dusted at substantially lower velocities in dust laden wind than in clear wind. Thus, an equilibrium amount of dust accumulated which was dependant only upon angle and wind velocity and not upon initial concentration of dust. Abrasion was also evident in the coverslips. It increased with wind velocity and angle of attack. It appears that an initial dust layer may help to protect PV surfaces from abrasion.

## INTRODUCTION

Within the last few years a consensus has been growing that NASA's primary objective for the early twenty-first century should be a manned expedition to Mars. This historic mission, and its precursors, will require the development of new technologies. The role of developing new technologies for power on the planetary surface has been assigned to the Lewis Research Center.

Mars has a diurnal cycle (24 hr, 37 min.) similar to that of Earth, and although it receives somewhat less sunlight than Earth ( $580 \text{ W/m}^2$ )[1], there is still sufficient solar flux to make photovoltaic power an important option. There are some concerns, however, about the durability of photovoltaic arrays in the Martian environment. Although there are a number of considerations such as large daily thermal cycles, ultra-violet radiation, and highly corrosive species in the soil, the predominant threat appears to be dust.

Dust is pervasive in the Martian environment as is evidenced by the pink color of the sky, thought to be due to suspended dust particles. It is transported widely about the planet. The top layer of soil from the Viking Lander 1 and 2 sites were virtually identical even though the landers were several thousand miles apart [2]. This is attributed to global dust storms which engulf the planet on a nearly annual basis. In addition there are numerous local and regional dust storms that affect some areas. During the storms the opacity of the atmosphere can increase to a value greater than 3, cutting off more than 85 percent of the light to the surface [3].

The dust storms, however, are relatively infrequent (limited to the global storms) over much of the planet. Rather than analyzing the performance of PV arrays during a storm, it is perhaps more important to ascertain whether their performance will be seriously degraded by deposited dust or abrasion. It is also important to assess whether deposited dust will likely be removed by natural processes. In a previous study it was found that dust particles will only be removed if they are subjected to substantial wind velocities (greater than 30 m/s) even if they are angled in their most favorable orientation to the wind (about  $45^\circ$ )[4]. The object of this study was to determine the effects of a Martian dust storm on the deposition, clearing, and abrasion of photovoltaic surfaces.

## METHODS AND MATERIALS

At this time no decision has been made about the type of PV cell which will be used in the early Mars exploration missions. It is assumed that PV cells will probably be protected with a coverslip, and that  $\text{SiO}_2$  is a likely coverslip material. It is also assumed that the coverslip will protect PV cells from adverse chemical reactions with the Martian environment, so the most important modes of performance degradation would be occlusion of incoming light by dust particles, and

abrasive degradation of the transparency of the coverslip. Thus, square glass coverslips, 2.54 cm on a side and 0.13 mm thick were used for the sample substrates. Although it may be advantageous to apply coatings to the coverslips, previous tests suggest that the coatings will have little effect on dust removal mechanisms [4], though they may affect coverslip abrasion. These substrates were mounted on sample holders which hold the substrate horizontally for characterization and initial dusting, and at angles of 0°, 22.5°, 45°, 67.5° or 90° for the tests (fig. 1).

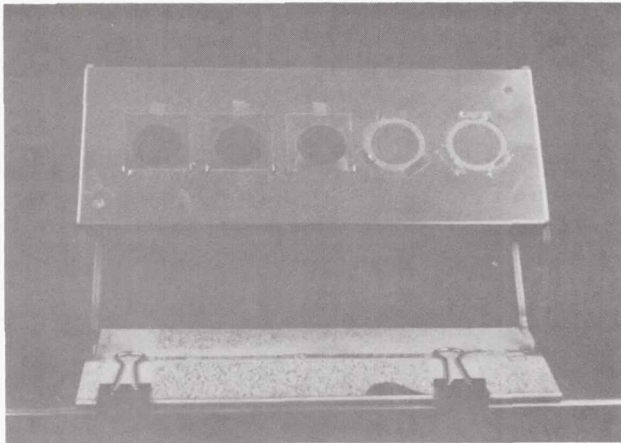


Figure 1.—Sample holder of the type used to test photovoltaic coverslips.

The dust used to coat the samples was a basalt known as "trap rock". This material is believed to be chemically similar to the dusts that are found on Mars. The fact that this dust has a grey-green color, however, suggests that there are significant differences. The particle size of this material ranged from about 5 - 38  $\mu\text{m}$ . Particles of this size could be elevated by the strong Martian winds present during storms, but would settle out during more common conditions. It should be noted that the purpose of these experiments was not to try to accurately simulate the Martian soil, but to determine the general effects of blowing dust on PV surfaces.

The initial layer of dust which was applied to half of the sample holders was deposited by placing them in a dusting chamber in which the dust was elevated using dry air and allowed to settle on the samples. Details about the method of dusting and characterization of the dust are described in detail elsewhere [5]. The uniformity and extent of the dust deposition was monitored optically. The specular transmittance was used as a probe of the extent of occlusion and abrasion. Power is also generated in PV cells from the diffuse light, and so the specular transmittance cannot be

converted directly to PV cell performance. Further references to transmittance in this work will refer only to the specular component. The specular transmittance was measured using an incandescent light source that shines into the photo-sensor of a Coherent Model 212 Power Meter. The sample coverslip was then placed between the source and the sensor and the percent decrease in the power was recorded.

In the case of initially clear samples the ratio of the final to initial transmittance ( $T_f/T_o$ ) was recorded. Note that this function goes to 1.00 when the slide totally clears, and to 0.00 when so much dust has been deposited that no light can be detected.

In the case of the initially dusted samples the situation is more complex. When assessing the clearing of a predusted slide with clear air, the dust clearing parameter  $(T_f - T_d)/(T_o - T_d)$ , where  $T_d$  is the transmittance of initially dusted samples before being subjected to the dust laden wind, is a useful indicator. This function goes to 1.00 if all of the dust is cleared off, and goes to 0.00 if none of the dust is removed. If there is a net accumulation of dust, this parameter becomes negative. Note that these are not the same conditions as the equation for the initially clear sample.

The winds on Mars were simulated using the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. The MARSWIT is a low pressure ( $\approx 10^2$  Pa) wind tunnel 14 m in length with a 1 m by 1.1 m by 1.1 m test section located 5 m from the tunnel's entrance. This flow-through wind tunnel is located within a 4,000  $\text{m}^3$  vacuum chamber. Its characteristics are described in detail elsewhere [6]. The samples were placed in the MARSWIT and tested under the conditions listed in table I.

**Table I -- Test conditions examined in the MARSWIT.**

Wind Speed m/s	Static Pres. Pa	Dyn. Pres. Pa	Time sec	Samples Pre-dusted
19	1000	7.0	45	yes
22	1000	9.3	45	no
55	1000	58	15	yes
58	1000	65	45	no
97	1000	180	5	half

The method used to simulate a Martian dust storm is illustrated in figure 2. The basaltic dust was fed through a hopper into the top of the MARSWIT, near the entrance. First the wind was generated in the

- 1) Chamber pumped down to 1kPa
- 2) Dust dropped past MARSWIT mouth
- 3) Flow initiated in MARSWIT
- 4) Dust laden wind strikes samples



Figure 2.—Experimental set-up to simulate a Martian dust storm.

MARSWIT at a velocity below that which would clear dust off of the pre-dusted samples. Then the hopper feed was started, dropping the dust into the air stream. Immediately thereafter the wind velocity was increased to the test conditions. The time reported in table I is the time spent at the maximum speed. The finer particles were carried along the wind stream and struck the samples, much as would happen during a dust storm on Mars. The MARSWIT was shut down before the hopper was turned off, so there was no time when high velocity clear air hit the samples. Both initially clean and initially dusted samples were included in these tests.

Some of the samples were gold coated and imaged in a Cambridge Model 200 Scanning Electron Microscope (SEM). Photomicrographs were made of samples both before and after dust was cleaned from the samples. Particle size distributions were determined using a Cambridge Quantimet 900 image analyzing computer.

## RESULTS AND DISCUSSION

The change in transmittance as a function of angle of attack for initially clear surfaces for wind velocities of 22, 58, and 97 m/s is shown in figure 3. It is apparent that the transmittance decreases as the angle of attack increases. For example, there is less than 5 percent degradation in the transmittance for samples held parallel to the wind, and a 17 to 36 percent degradation for those held perpendicular to the wind. Higher velocity winds were found to also produce larger decreases in transmittance.

The transmittance could be degraded by two mechanisms. First, dust could accumulate and occlude the surface. Second, the surface could be abrasively

damaged giving rise to more scattering and less transmittance. Alternately, both mechanisms could be at work. Samples were examined using (SEM) for evidence of degradation. The photomicrographs in figure 4 show that, for the 97 m/s initially clear samples,

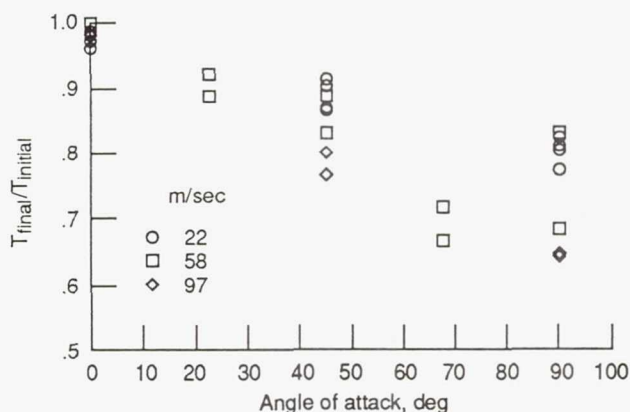
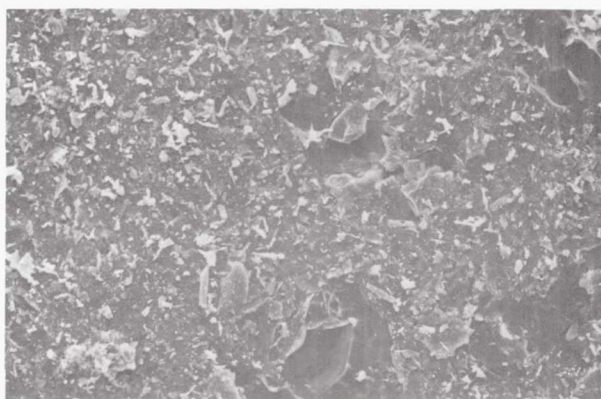


Figure 3.—Change in coverslip transmission as a function of angle of attack for initially clear samples.



(a) Angle of attack = 0°.



(b) Angle of attack = 90°.

Figure 4.—Scanning electron micrographs of coverglass surfaces subjected to 97 m/s dust laden winds.

the abrasive damage increased dramatically as the angle of attack increased. Other photomicrographs supported the intuitive notion that increased wind velocity also caused increased abrasion.

Dust was carefully removed from the surfaces of some of the samples and their transmittance was remeasured. These results indicate that, in the extreme case of initially clear coverslips subjected to 97 m/s dust laden wind, about half of the transmittance degradation was due to abrasion. Initially dusted coverslips subjected to 55 m/s dust laden wind were similarly measured. In this case the abrasive degradation was minimal. Thus, at high wind velocities abrasion does have a significant degradative effect on coverslip transmittance.

Figure 5 shows the ratio of the transmittance of dusted samples to their initial transmittance. Because of size limitations of the dusting apparatus, each wind tunnel test required two dust deposition runs to prepare samples. Only the 55 m/s MARSWIT test show a large variation in  $T_d$ . The vast majority of the transmittance data lie between 0.57 and 0.72.

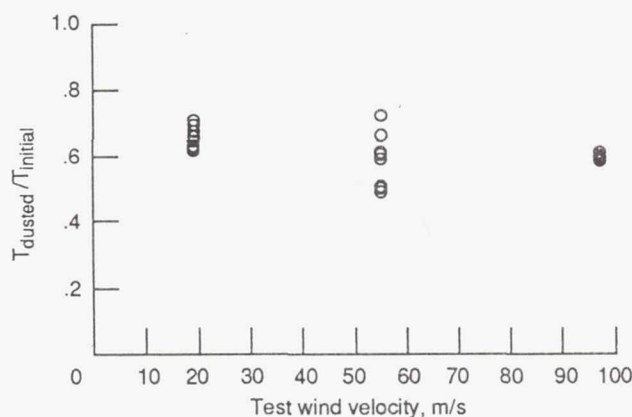


Figure 5.—Transmission of predusted samples before subjection to dust-laden wind.

Upon subjecting the samples to the dust-laden wind, all of the samples except one had dust removed from the surface, that is, they became more transmitting. This is illustrated in figure 6 which shows the dust clearing parameter  $((T_f - T_d) / (T_o - T_d))$  as a function of angle. The single data point which was negative had a value of -0.06, and had an angle of  $0^\circ$  subjected to a 19 m/s wind. It is interesting that all of the other samples cleared at 19 m/s, because previous tests indicated that, when clear air was blown across the samples, a velocity greater than 30 m/s was required to clear off the samples [4]. This indicates that wind-laden particles striking surface particles is an efficient mechanism of dust removal.

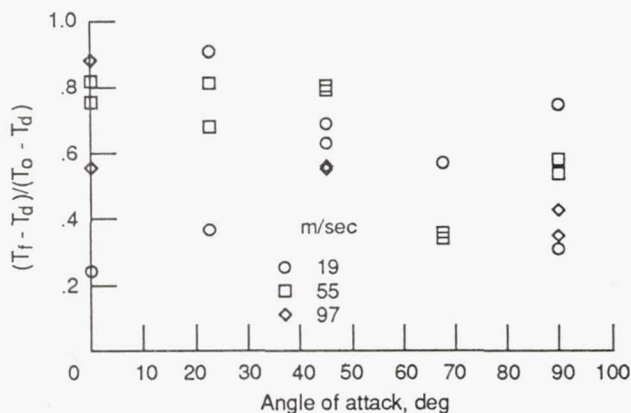


Figure 6.—Dust clearing as a function of angle for initially dusted samples subjected to dust laden winds at 19, 55, and 97 m/s.

The general dependence upon angle for dust clearing seems to be an additive combination of experiments in which dust laden wind encounters clean initial surfaces, and those in which clear wind encounters initially dusted surfaces (as described in reference [4]). Dust on  $0^\circ$  (horizontal) surfaces is neither cleared easily by clear wind, nor is there much deposited by dust-laden wind. Dust is cleared best in clear wind when the angle is approaching  $45^\circ$  [4], but dust is deposited more with increasing angle. Thus, when the two effects act together, there is the most clearing in the  $22.5^\circ$  case, which steadily tapers off to the  $90^\circ$  (vertical) case. (There was an ambiguity in determining  $T_o$  for the  $67.5^\circ$ , 55 m/s test which casts suspicion on those anomalously low data.)

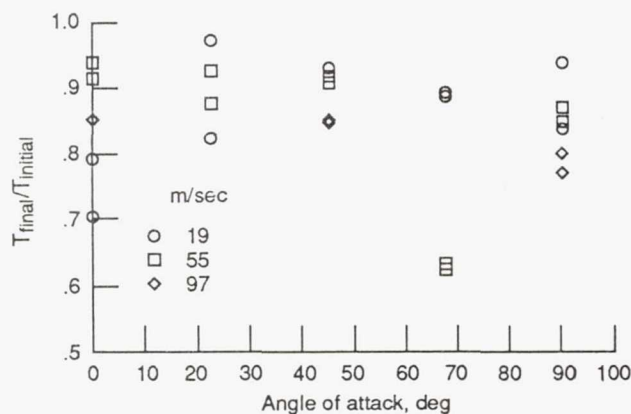


Figure 7.—Change in coverslip transmission as a function of angle of attack for initially dusted samples.

Figure 7 shows the ratio of the final to initial (before dusting) transmittance of the initially dusted samples. It appears as though there are effects of having dust already deposited on the samples before they are subjected to the dust-laden wind. The average  $T_f/T_o$  value for the initially clear samples with an attack angle of  $90^\circ$  which were subjected to the 97 m/s dust-laden wind is about 0.65, however, the average  $T_f/T_o$  for the corresponding initially dusted sample is about 0.78. Thus, initially dusted samples had higher final transmission than did the initially clear sample. The explanation of this unexpected behavior must lie in the effects of abrasion. The most likely scenario is that a significant portion of the energy which, in the clear surface case, fractures the surface, in the initially dusted case instead is diverted into removing particles from the surface.

It appears as though the amount of dust which will be on a surface after a significant amount of time in dust-laden wind is independent of the amount of dust initially on the surface. The exposure times in this experiment were very short, typically 45 seconds. And yet within this short time there was little difference between the amount of dust remaining on an initially clean surface and an initially dusty surface. This leads to the expectation that an equilibrium concentration of dust on the surface is quickly established which varies with wind velocity, suspended dust, and surface angle, but not upon initial dust concentration.

The distributions of sizes of the particles which remained on the slide after the wind tests as determined by the Quantimet data are shown in Table II. Three classes of distribution are compared, the initial dust distribution, the dust distribution on initially clear surfaces, and the dust distribution on initially dusted surfaces.

An interesting trend appears in the samples which were initially clear, but then were subjected to a 97 m/s dust-laden wind. At the  $0^\circ$  attack angle, the particle size distribution is similar to the initial distribution. But as the angle is increased to  $45^\circ$  and then to  $90^\circ$ , the percentage of small particles increases. A plausible explanation of this trend can be inferred if the deposition processes are examined. At  $0^\circ$ , dust is deposited because of turbulence induced by irregularities on the surface. Within the turbulent region the velocity is somewhat lower than within the laminar region, and so particles tend to settle out, somewhat gently, onto the surface. When the  $45^\circ$  and  $90^\circ$  samples are considered, the inertial mass of the particles will not permit them to be carried along in the laminar flow, but

**Table II -- Particle size distribution of dust particles left on samples after MARSWIT tests.**

Particles	<4 $\mu\text{m}$	4-8 $\mu\text{m}$	8-12 $\mu\text{m}$
Initial	84.1 %	11.8 %	3.6 %
97 m/s, $0^\circ$ initially clear	84.8	12.1	3.1
97 m/s, $45^\circ$ initially clear	89.9	7.5	2.5
97 m/s, $90^\circ$ initially clear	92.3	5.8	1.9
55 m/s, $0^\circ$ initially dusted	88.3	7.5	4.2
55 m/s, $45^\circ$ initially dusted	85.7	10.6	3.7

their momentum will cause them to crash into the surface. However, if this were the case, a preponderance of large particles would be expected, because of their smaller surface to mass ratio. The simplest explanation for how more large particles can hit the surface and yet result in more small particles is if the large particles are in fact agglomerates which shatter when they strike the surface.

The results using initially dusted samples subjected to 55 m/s dust laden wind can also be analyzed by assuming a combination of dust clearing and dust depositing processes. Dust clearing is expected to favor the clearing of large particles over the clearing of small. This is because dust adhesion is a surface phenomenon, and the surface to volume ratio of smaller particles is greater than that of larger. If a particle layer is already present on the sample surface, then the larger agglomerates which strike the sample will encounter other dust grains. Some of the impact energy will be transformed into kinetic energy of ejected particles, and as a result agglomerates will be less likely to break-up. The turbulent layer above the  $0^\circ$  samples will deposit particles from the wind, but areas of high local velocity will also clear off some portion of the already deposited layer. The transmission measurements show that this is a net erosional process. The particle size measurements indicate that, it is the midrange of particles which are depleted. Both the small particles (less than 4  $\mu\text{m}$ ) and the larger particles (greater than 12  $\mu\text{m}$ ) tend to build

up. At 45° both the clearing and the deposition happen at a more rapid rate. The percentage of larger particles drops to the initial value, but the smaller particles still increase slightly with respect to their initial value. One would expect the small particles to dominate in this case because the agglomerates should be split upon impact into small pieces which would not be easily removed. It is difficult to explain why the data do not bear this out, indicating a need for further study of this area.

### CONCLUSION

The tendency of blowing dust to stick to a PV coverslip surface was found to increase with angle of attack from 0° to 90°. In addition, abrasion of the coverslip increased with wind velocity and angle of attack. When PV coverslips are subjected to dust laden wind an equilibrium amount of dust accumulation is attained which is only dependant upon angle of attack and wind velocity. Dust is partially cleared from surfaces at substantially lower velocities in dust laden wind than in clear wind. Paradoxically, an efficient method to minimize one of the most important modes of degradation in the Martian dust environment, that of abrasion, might be to initially cover the surfaces with a small amount of dust.

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